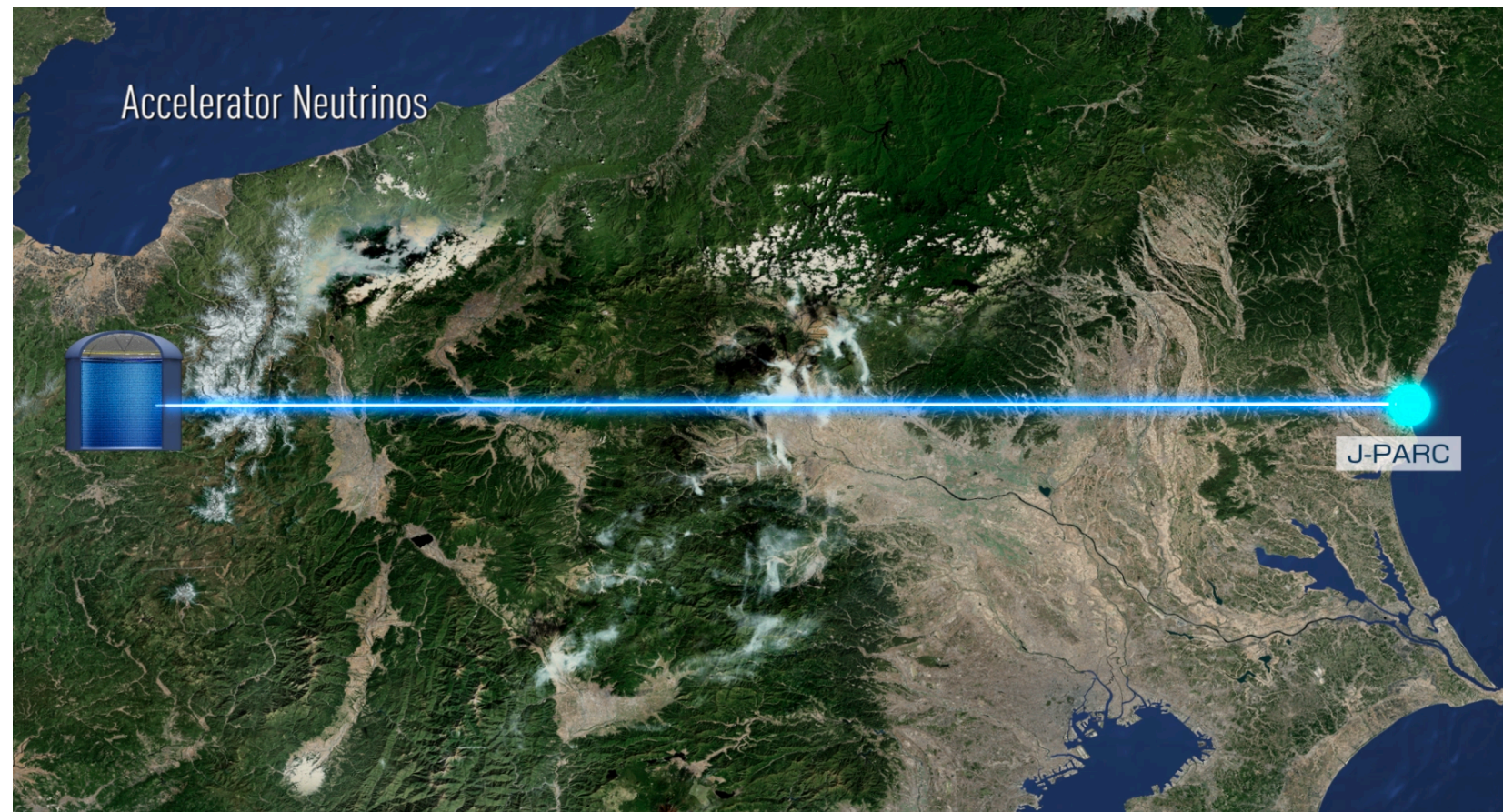


# LBL neutrino oscillation experiment by Hyper-Kamiokande

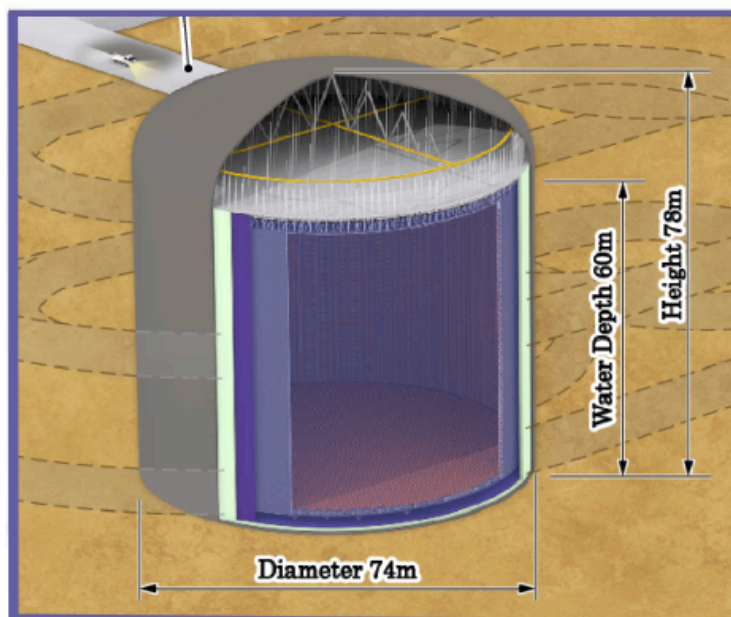
T. Nakadaira  
(KEK IPNS/J-PARC)





# Outline

- Hyper-Kamiokande experiment
- Project status
- Long base-line experiment by Hyper-K
- Physics prospects



**Hyper-Kamiokande**  
(Univ. of Tokyo ICRR, Gifu)

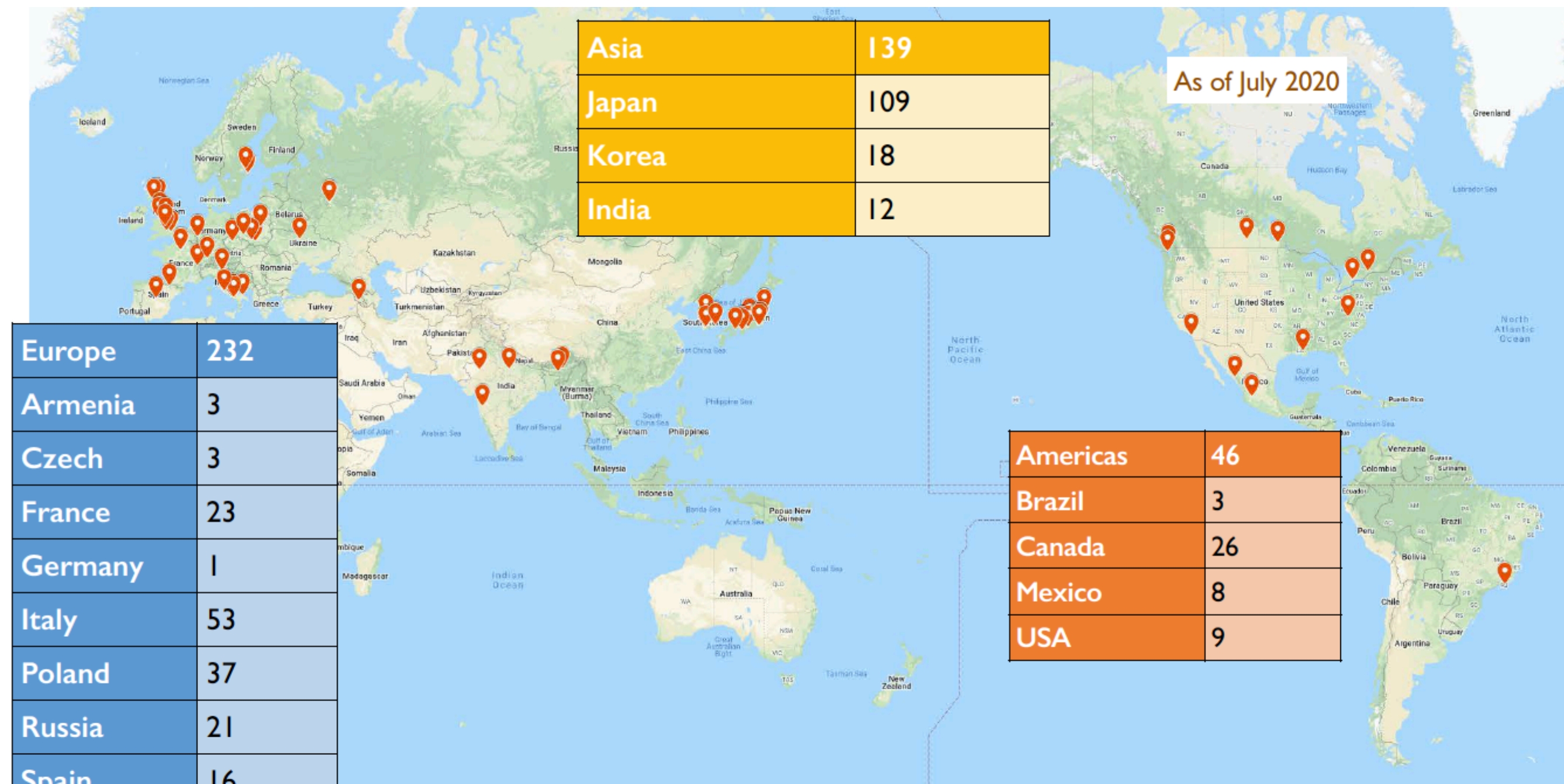


**J-PARC Main Ring**  
(KEK-JAEA, Tokai)





# Hyper-Kamiokande Collaboration

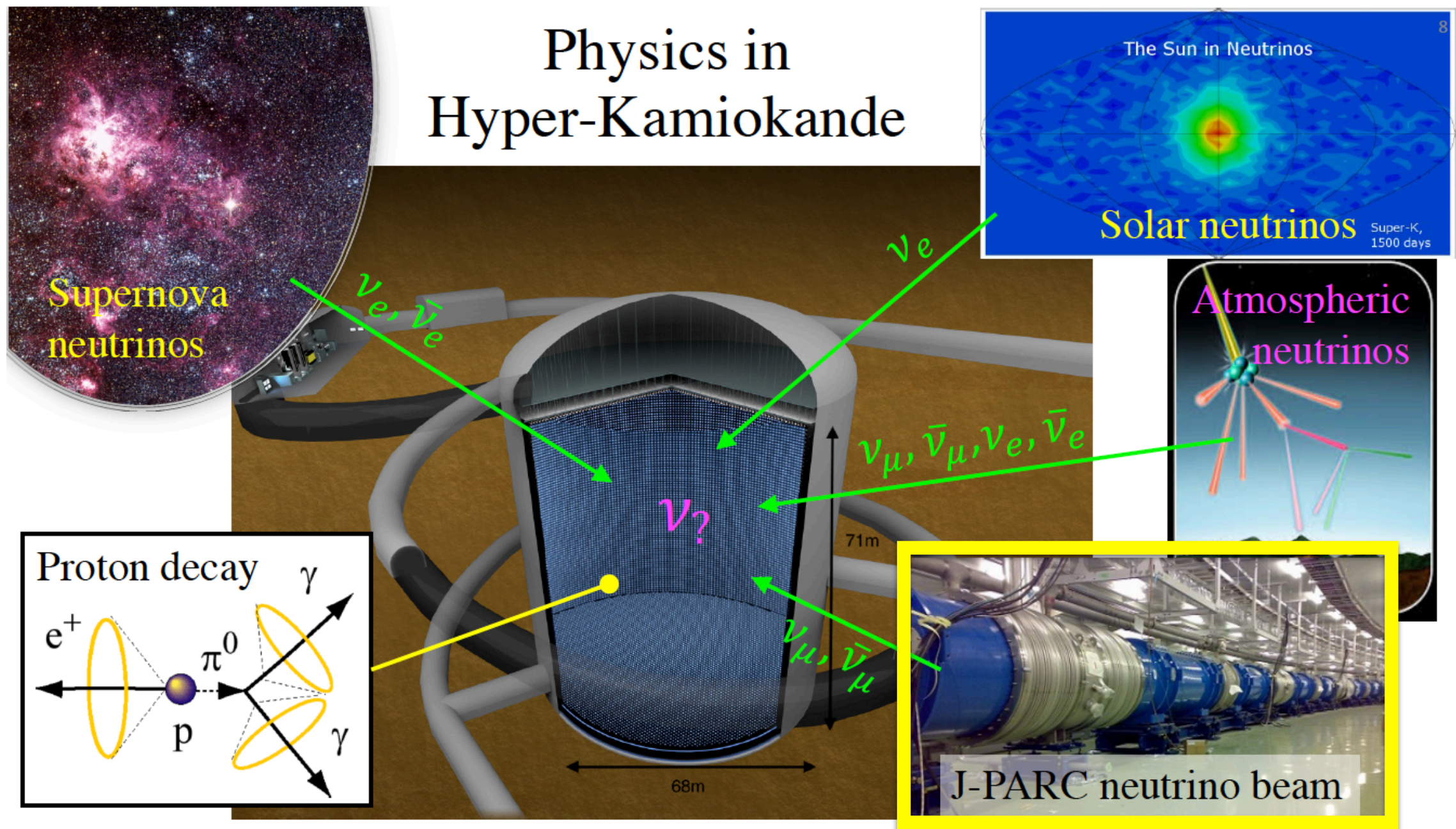


*19 countries, 90 institutes, ~420 people*





# Hyper-Kamiokande Experiment



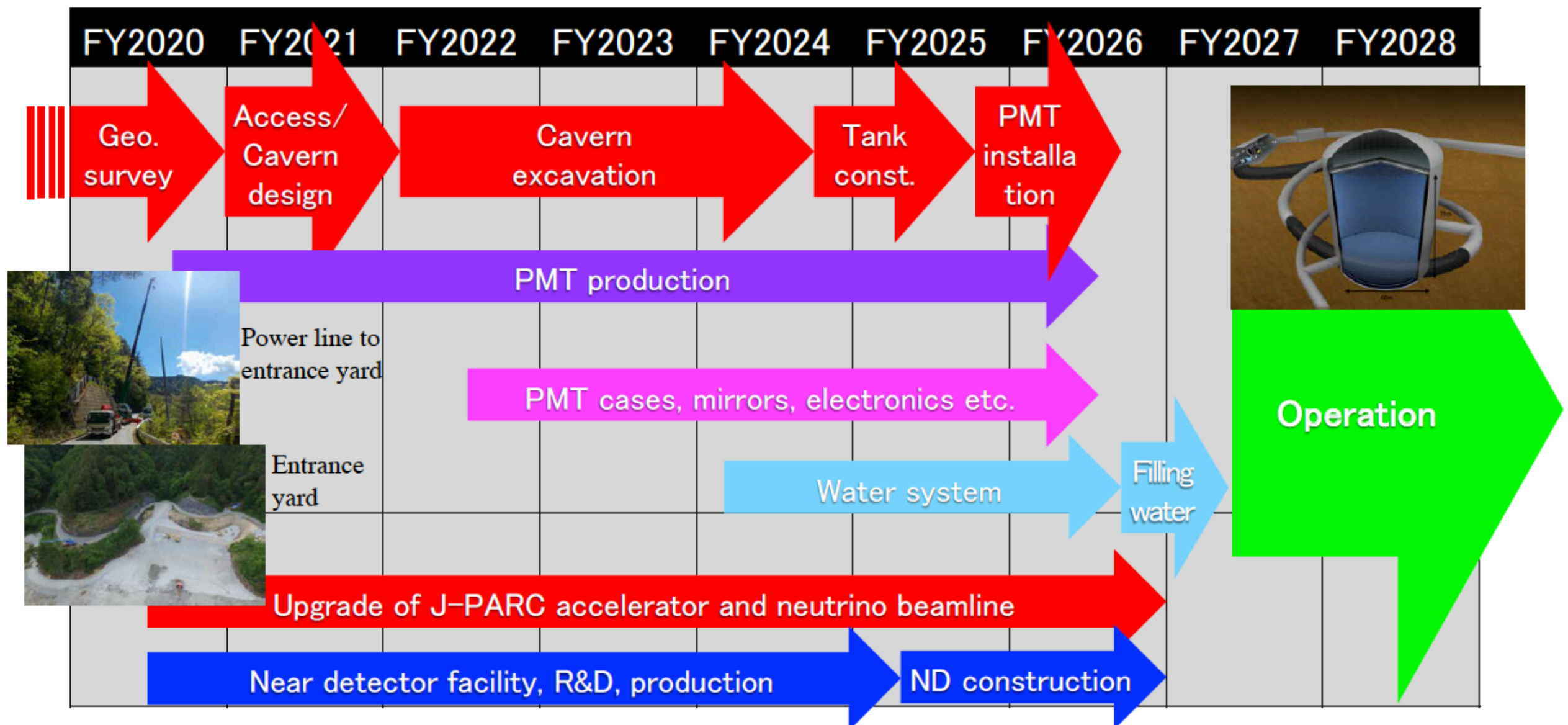
- Fiducial mass = 188 kton ( $\times 8.4$  w.r.t Super-K)
  - 1.3MW Neutrino beam ( $\sim 500$  kW achieved so far)
- $\Rightarrow$  **LBL oscillation measurement w/  $\sim \times 20$  statistics**



# Hyper-Kamiokande Project

- New Huge Water Cherenkov detector  
+ J-PARC accelerator & neutrino beam upgrade
- **Construction started from 2019!**

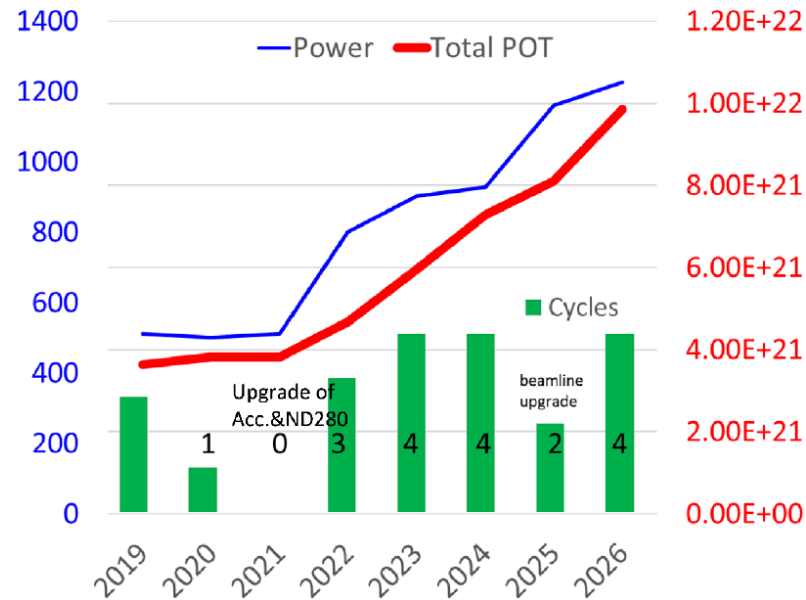
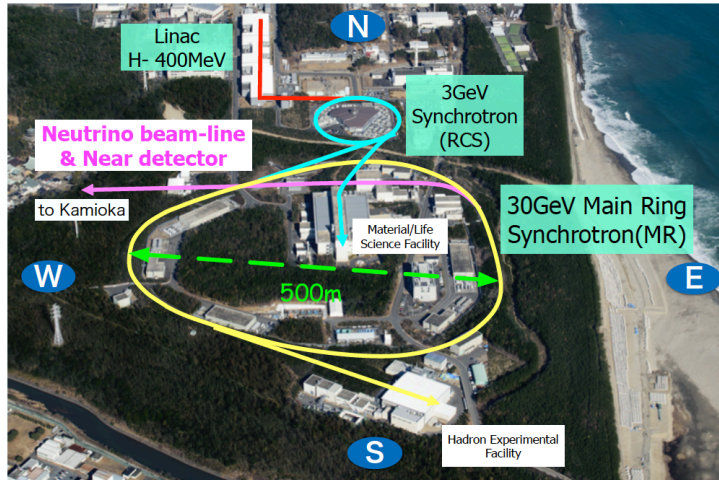
by Univ. of Tokyo and KEK.





# J-PARC upgrade for HK era.

- Straight-forward extension from T2K to HK is planned.



**Stable 1.3MW beam**  
 6 month/year  
 $\Rightarrow \sim 2.7 \times 10^{22}$  POT  
 in 10 years  
 is expected.

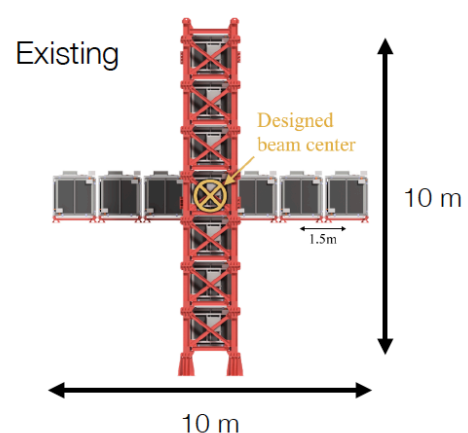
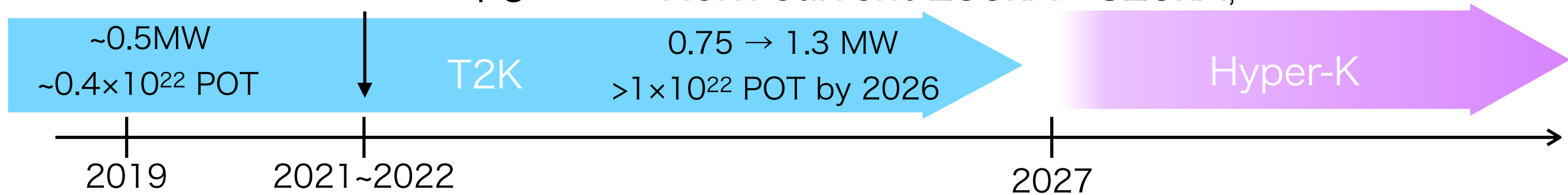
- MR PS upgrade

Rep. rate 0.40Hz  $\rightarrow$  0.75Hz

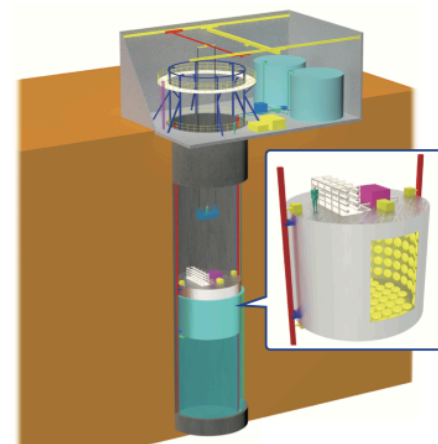
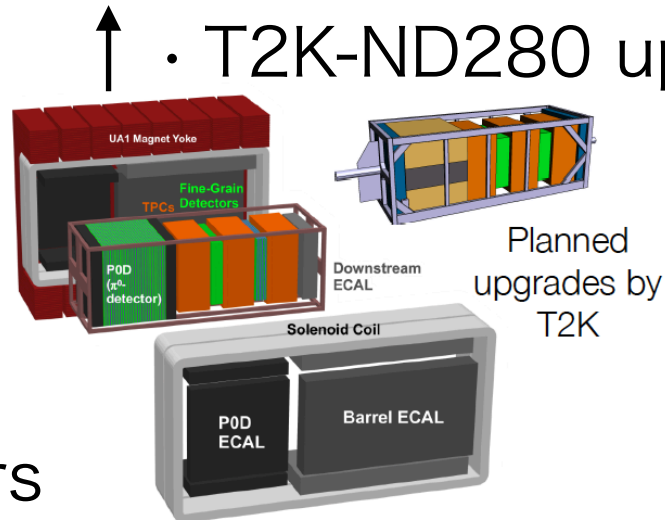
- Neutrino beam-line upgrade

- Upgrade of MR-RF, NU target, ...

- Horn current 250kA  $\rightarrow$  320kA,



- Near Detectors



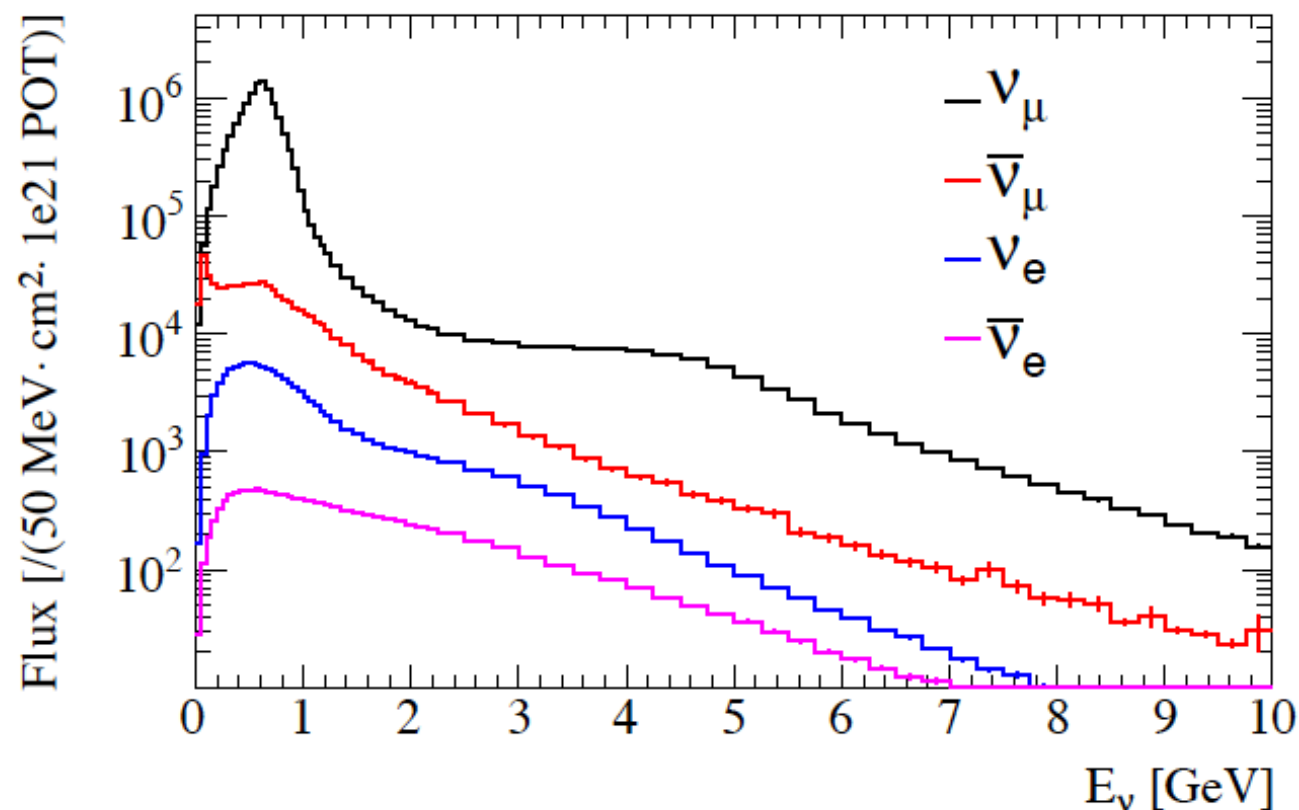
- **IWCD**  
 : New WC detector  
 near J-PARC (proposed).



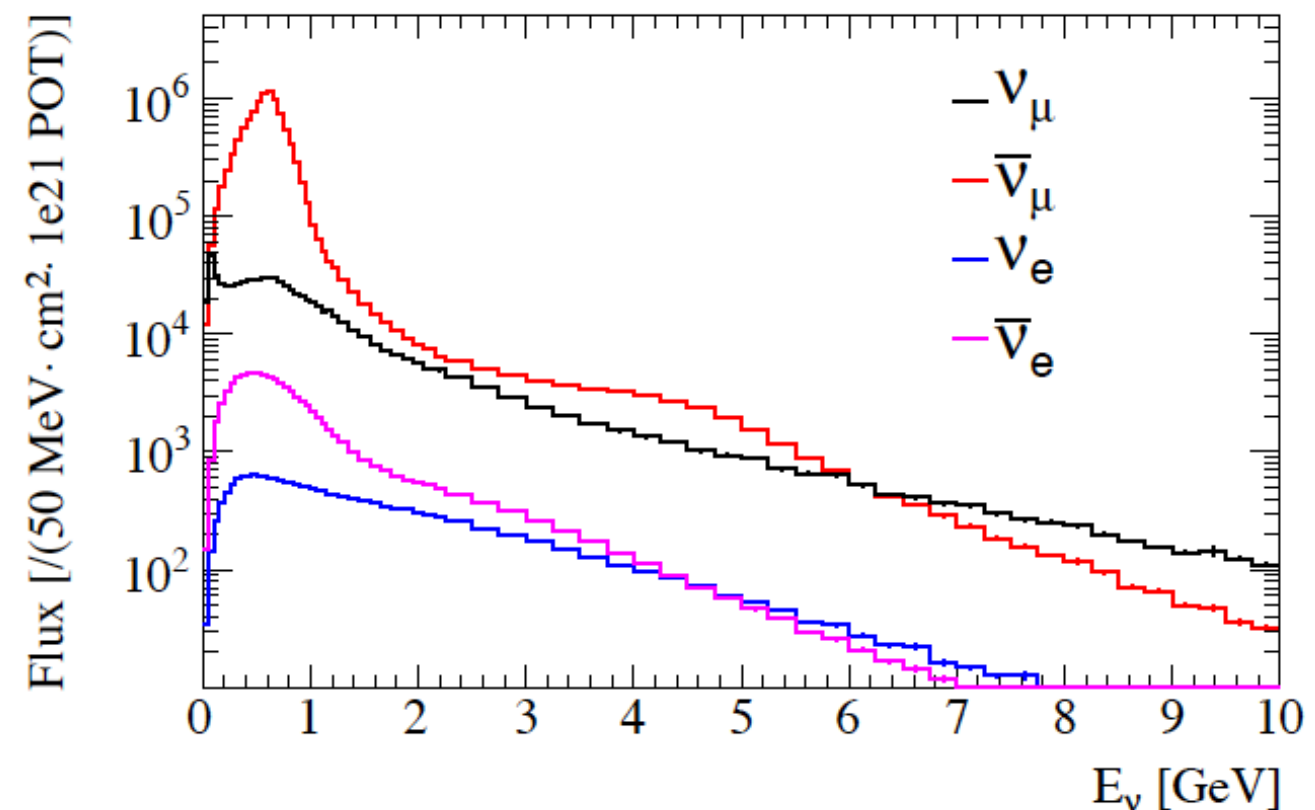
# LBL Neutrino oscillation @ HK

- Combined measurement of 4 neutrino oscillation modes at Sub-GeV energy.
  - $\nu_\mu$  disappearance and  $\bar{\nu}_\mu$  disappearance
  - $\nu_e$  appearance and  $\bar{\nu}_e$  appearance
- Measurement for  $\nu_\mu$ -beam and  $\bar{\nu}_\mu$ -beam, respectively.
  - ~0.6GeV narrow band beam by Off-axis method.
  - HK and SK is located at symmetric position w.r.t beam-axis.
    - Neutrino flux for HK can be estimated well from T2K experience.

Hyper-K Flux for Neutrino Mode



Hyper-K Flux for Antineutrino Mode

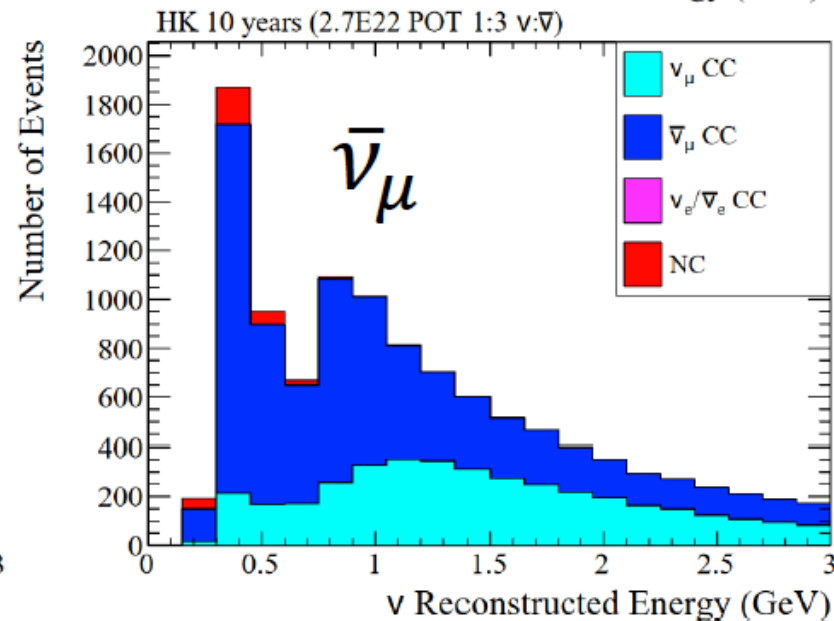
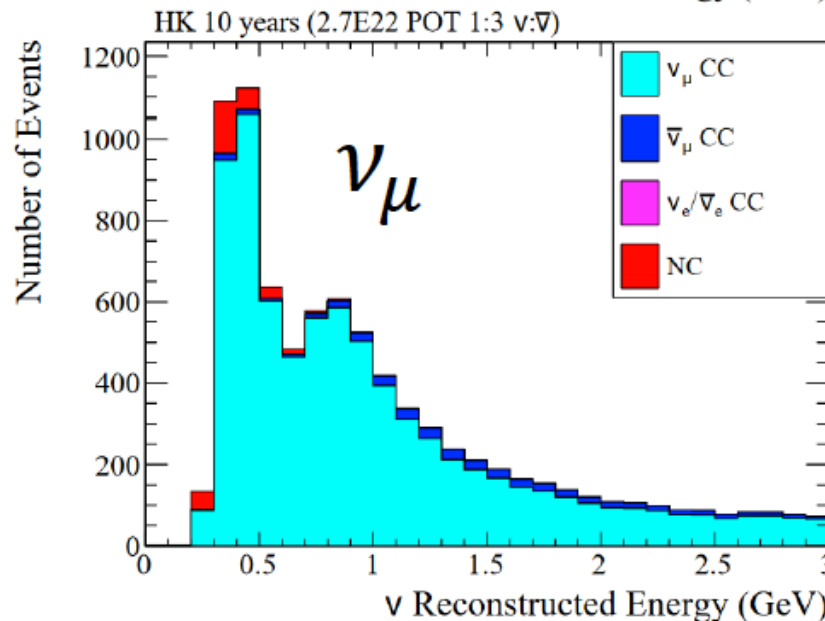
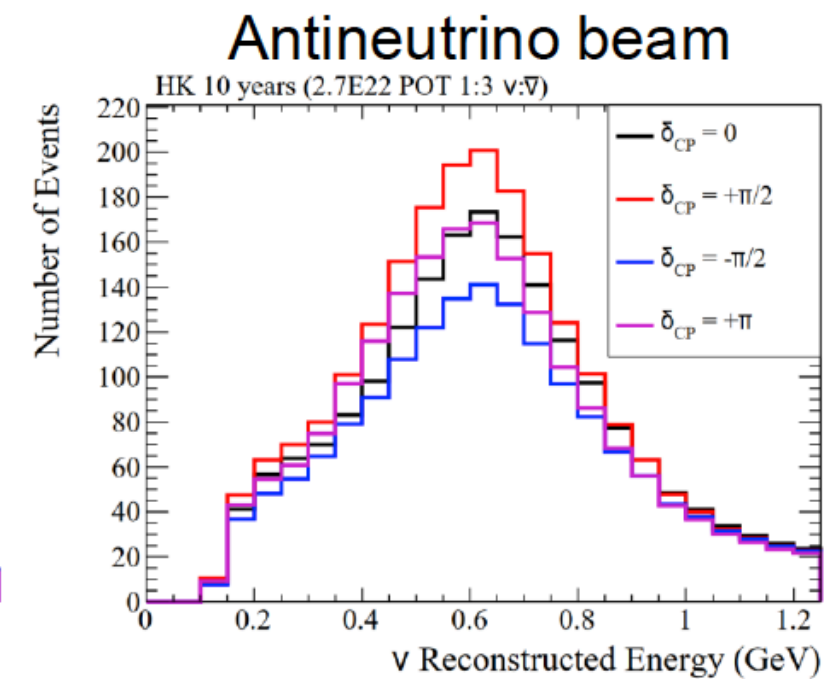
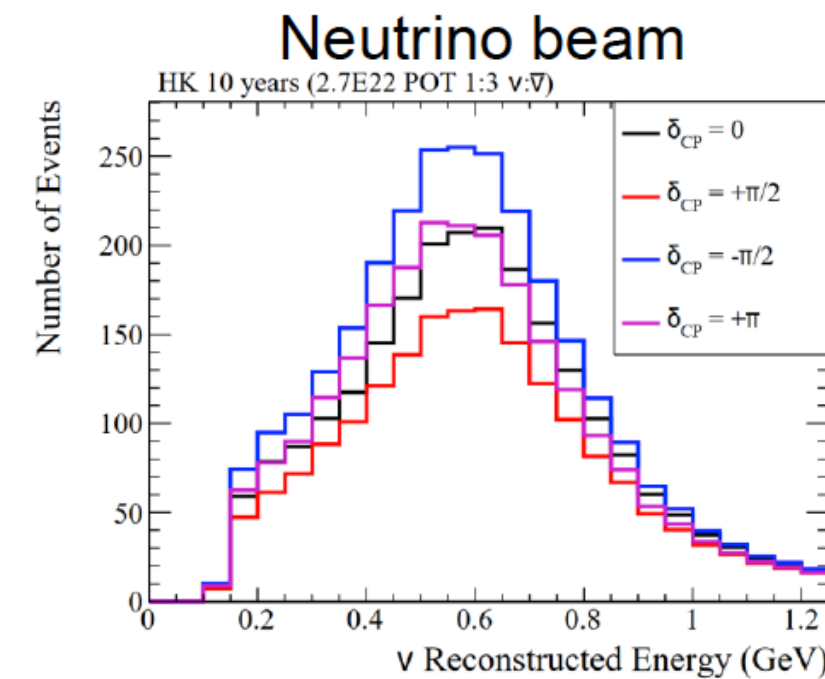




# Expected Far-detector event samples

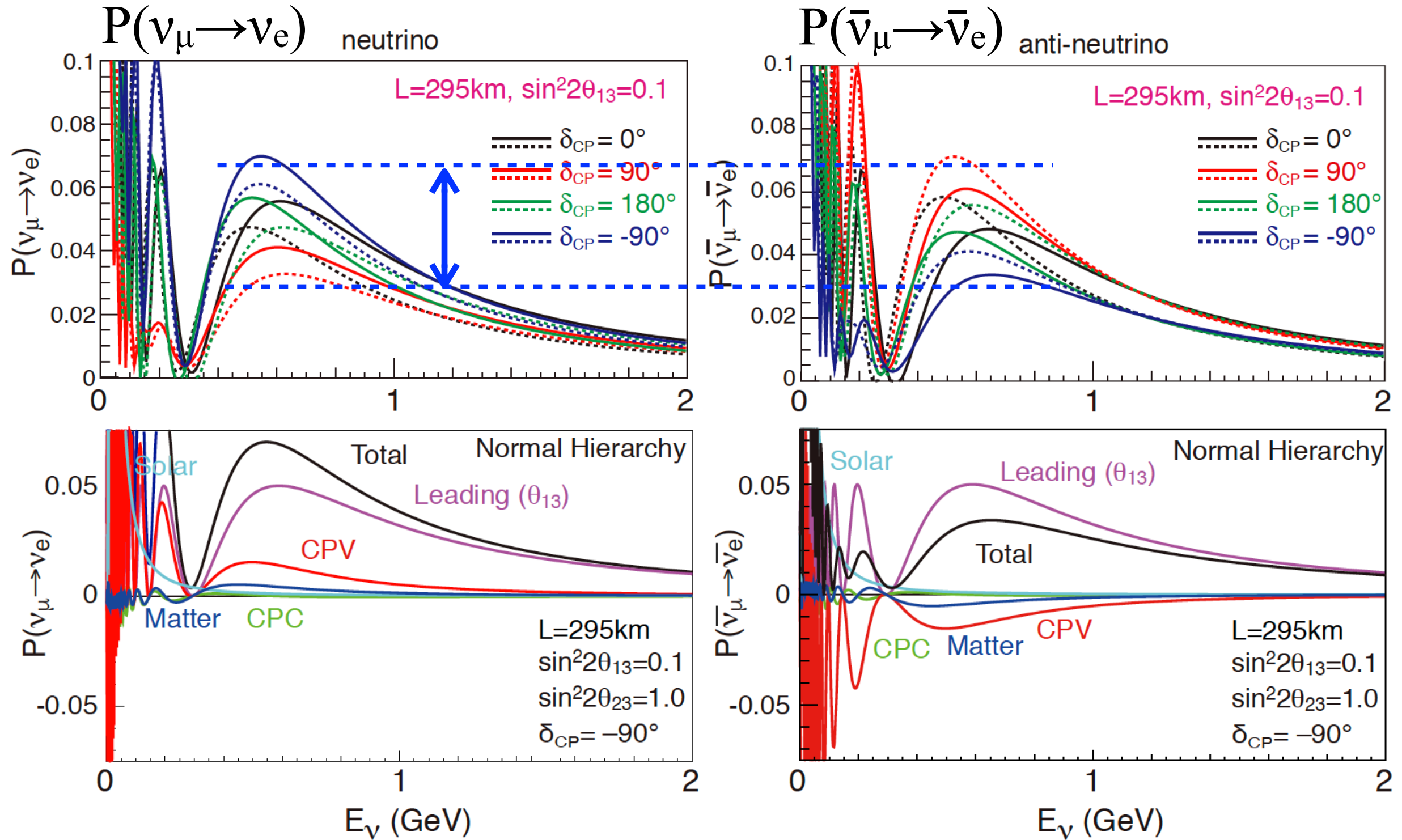
- Estimated for  $2.7 \times 10^{22}$  POT (10 years operation)  
assuming  $\nu$ -beam :  $\bar{\nu}$ -beam = 1 : 3
- Expected candidates for  $\sin\delta_{CP}=0$  scaled from SK MC.
  - 2300  $\nu_e$  events
  - 1900  $\bar{\nu}_e$  events
  - 9300  $\nu_\mu$  events
  - 12300  $\bar{\nu}_\mu$  events

**High statistics  
samples  
for  
neutrino oscillation  
measurement**





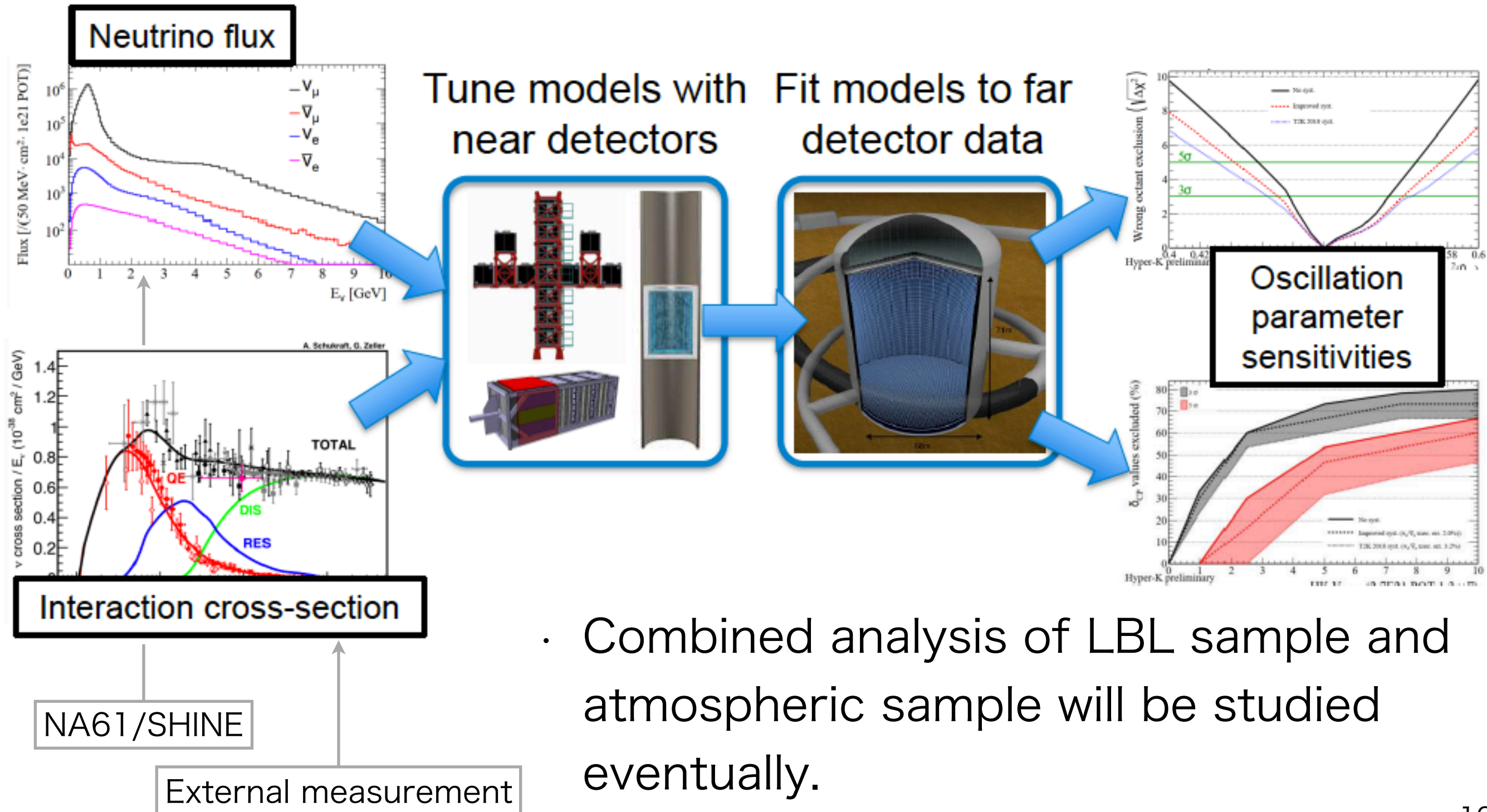
# Expected CPV in $\nu_e$ appearance



$$\frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \simeq -0.28 \sin \delta_{CP} + 0.09$$

# Analysis Method

- Prospects for physics goals are estimated based on T2K Analysis Method, at this moment.



- Combined analysis of LBL sample and atmospheric sample will be studied eventually.

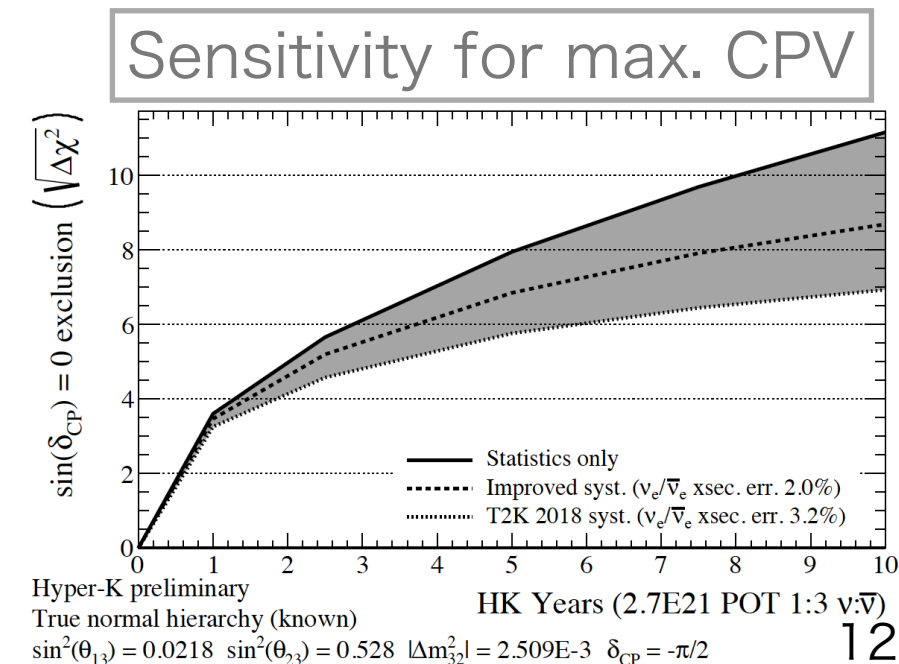
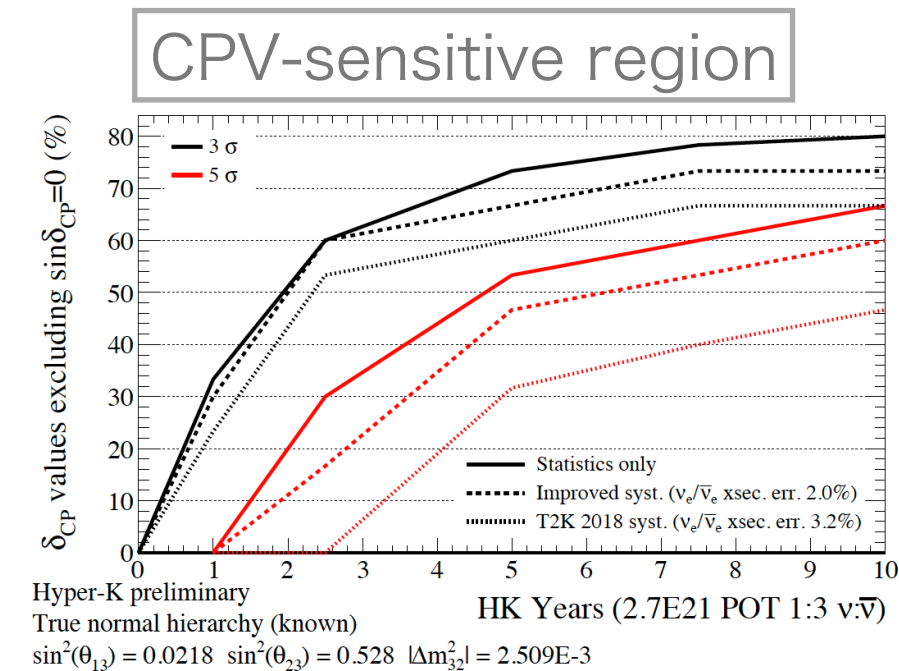
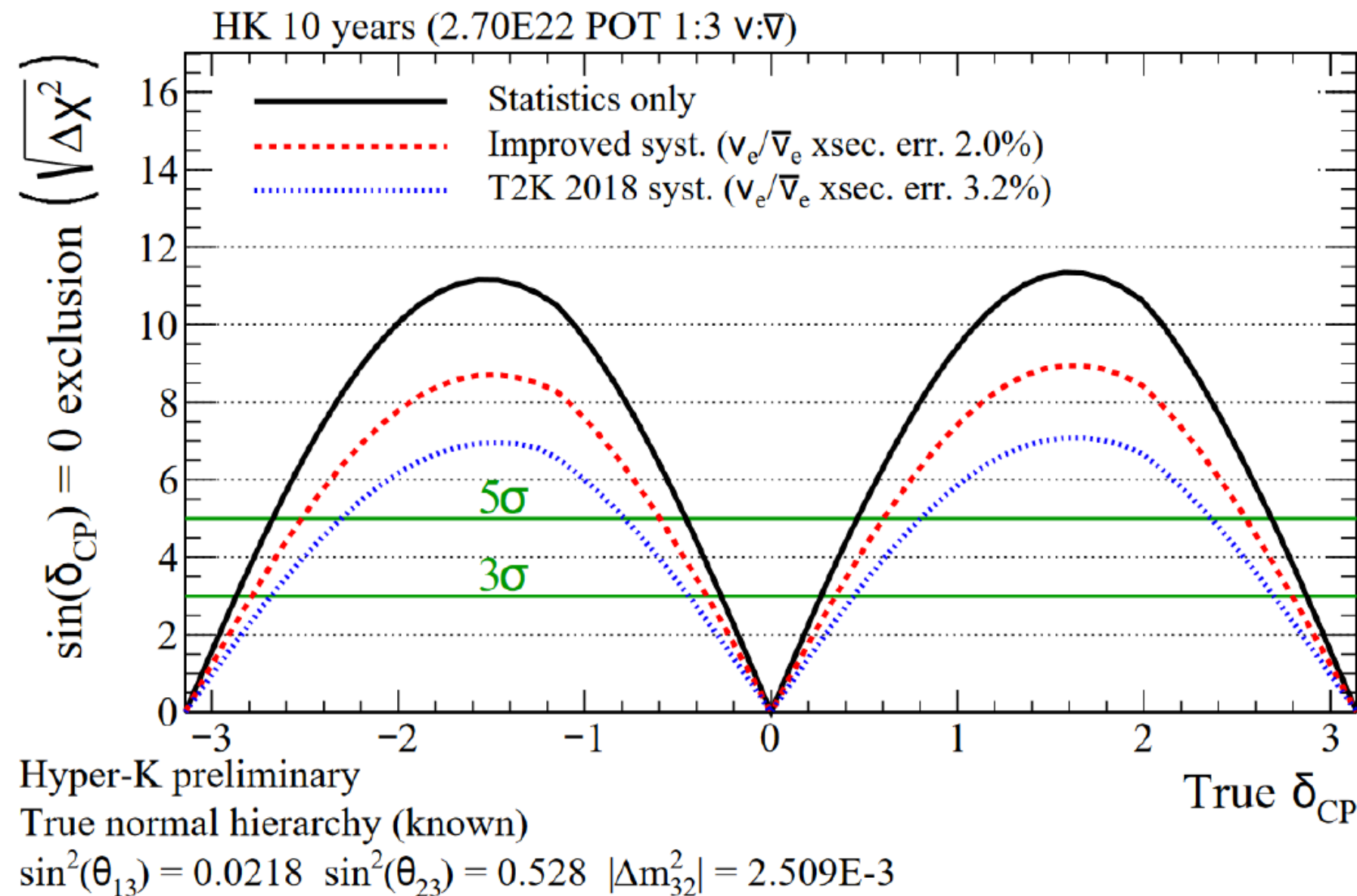


# Expected physics outcomes

- Sensitivities for oscillation parameters are estimated assuming for two systematic error assumptions.
  - (1) **“T2K-2018” uncertainties**
    - Systematic error estimation method/inputs are applied to HK event samples.
  - (2) **“Improved” uncertainties**
    - (flux×cross-section) and far-detector systematics is expected to be scaled by  $1/\sqrt{N}$ . ( $N=8.7$ )
    - Effect of ND280 upgrade and IWCD measurements.
      - Factor 2~3 reduction for CC interaction uncertainties, and ~10% uncertainties for NC interactions.
    - $\nu_e / \bar{\nu}_e$  cross-section ratio uncertainties are varied from ~3.6% to 1% to assess its impact.
    - No parameter is allowed to have an uncertainties of less than 1%.

# Prospects for CP violation search

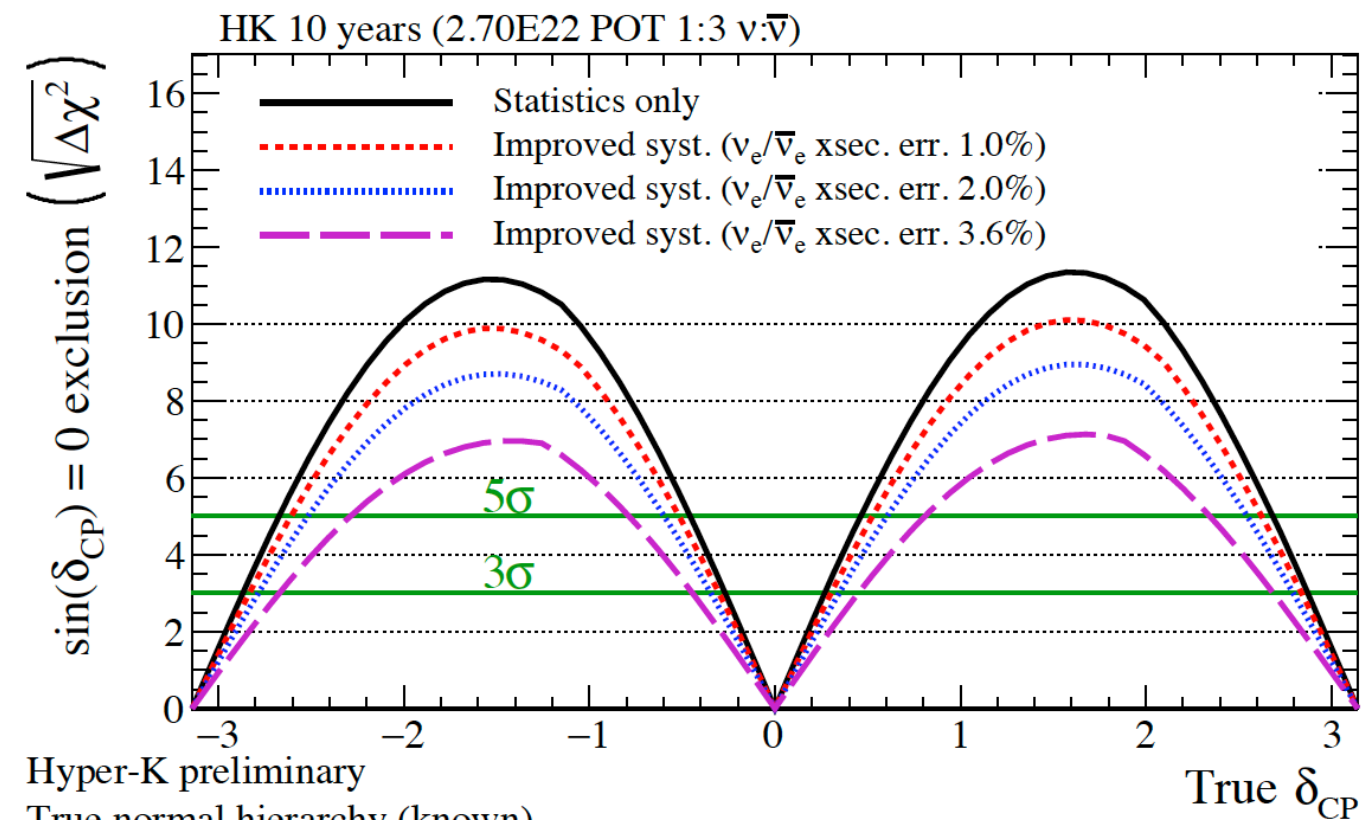
- Sensitivity to exclude  $\sin\delta_{CP}=0$  assuming MH is known.
  - 60% of parameter space can be explored with  $5\sigma$  in 10 years.
  - For true  $\delta_{CP}=-\pi/2$  case,  $\sin\delta_{CP}=0$  can be excluded in 2~3 years.





# Prospects for CP violation search

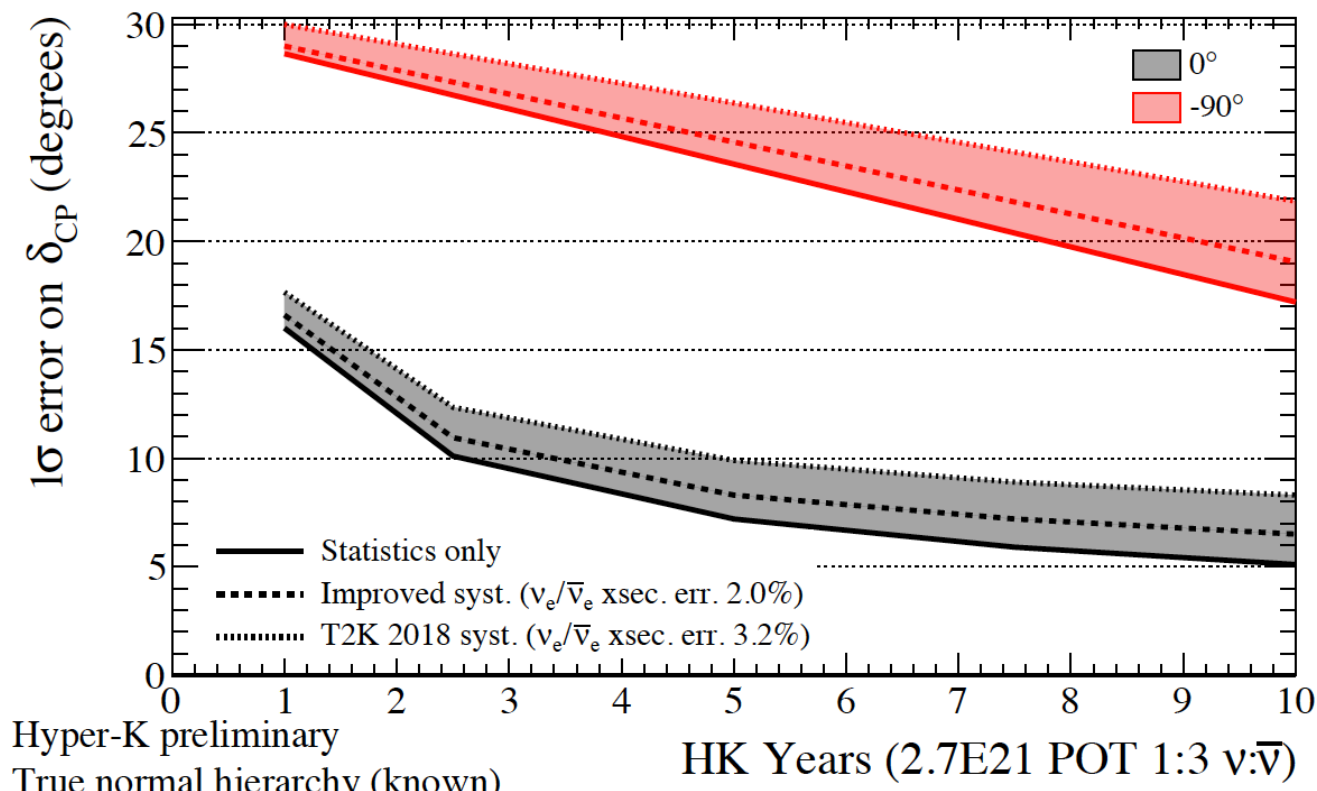
- Uncertainty on  $\nu_e / \bar{\nu}_e$  cross-section has large effect for CPV search.
  - Current theory uncertainty :  $\sim 3.2\%$
  - To be studied as much as possible.
- Expected precision of  $\delta_{CP}$  measurement. ( $1\sigma$  error)
  - $\sim 7^\circ$  for true  $\delta_{CP}=0^\circ$
  - $\sim 20^\circ$  for true  $\delta_{CP}=-90^\circ$



Hyper-K preliminary

True normal hierarchy (known)

$\sin^2(\theta_{13}) = 0.0218$   $\sin^2(\theta_{23}) = 0.528$   $|\Delta m_{32}^2| = 2.509E-3$



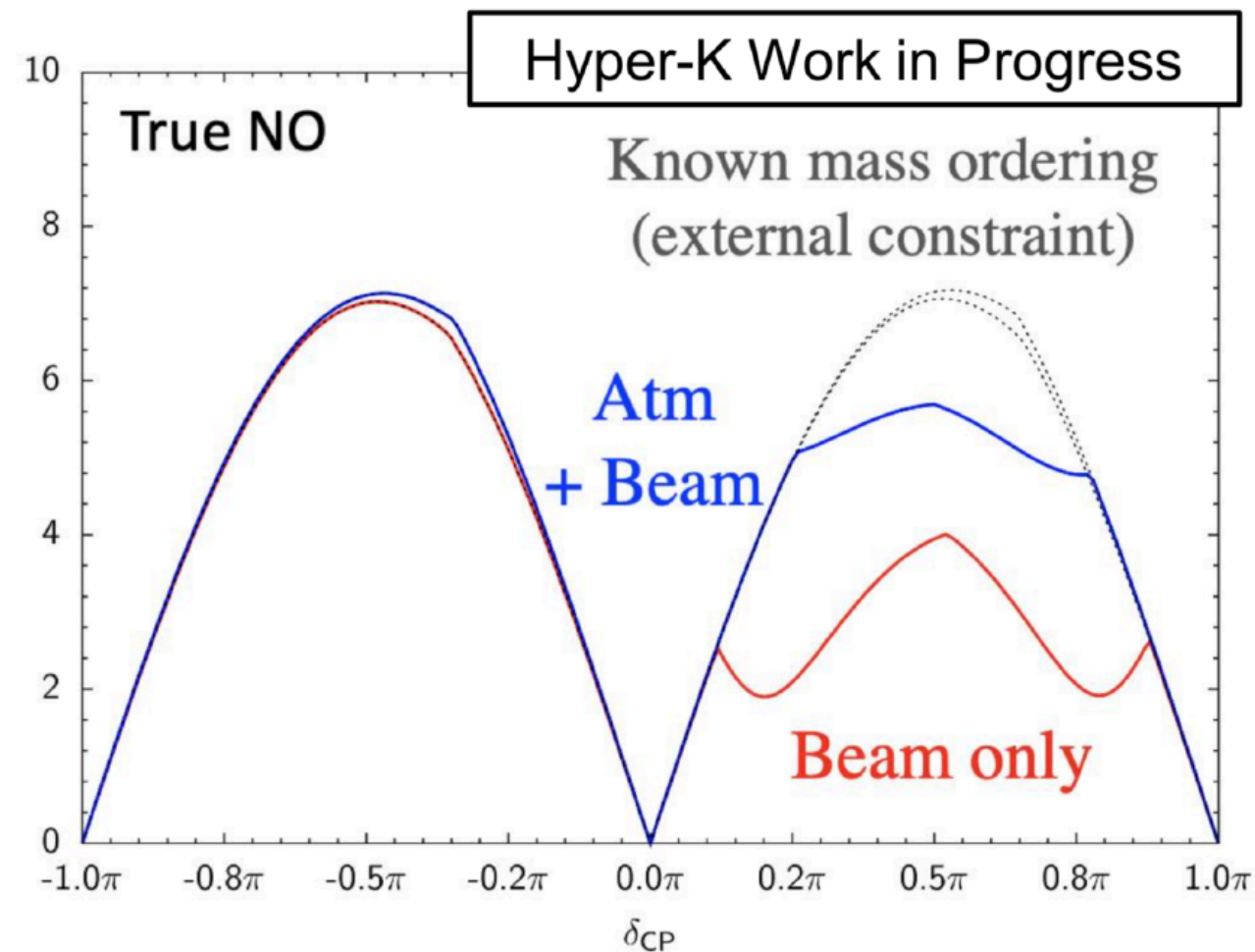
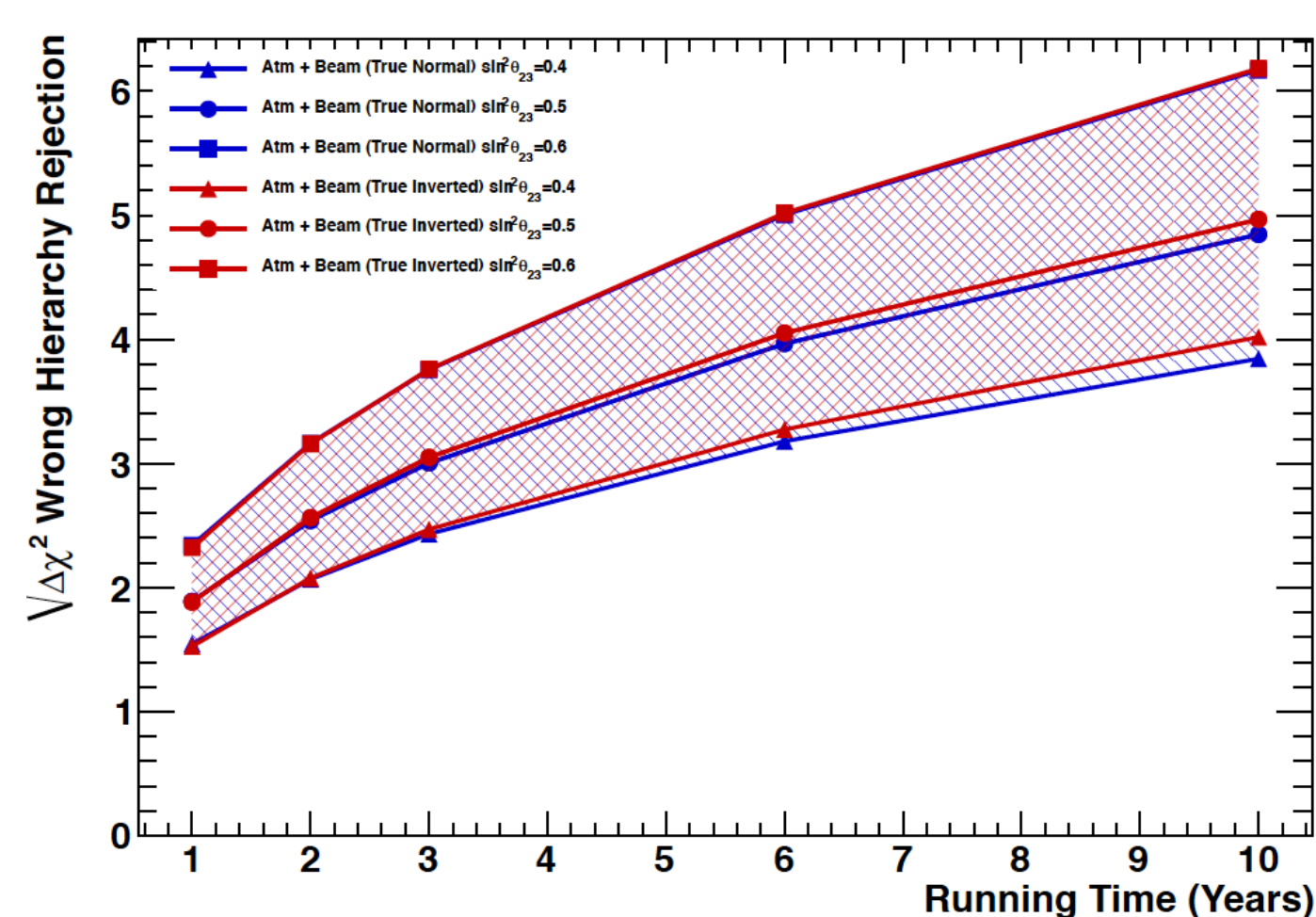
Hyper-K preliminary

True normal hierarchy (known)

$\sin^2(\theta_{13}) = 0.0218$   $\sin^2(\theta_{23}) = 0.528$   $|\Delta m_{32}^2| = 2.509E-3$

# Combined analysis with Atmospheric $\nu$ samples.

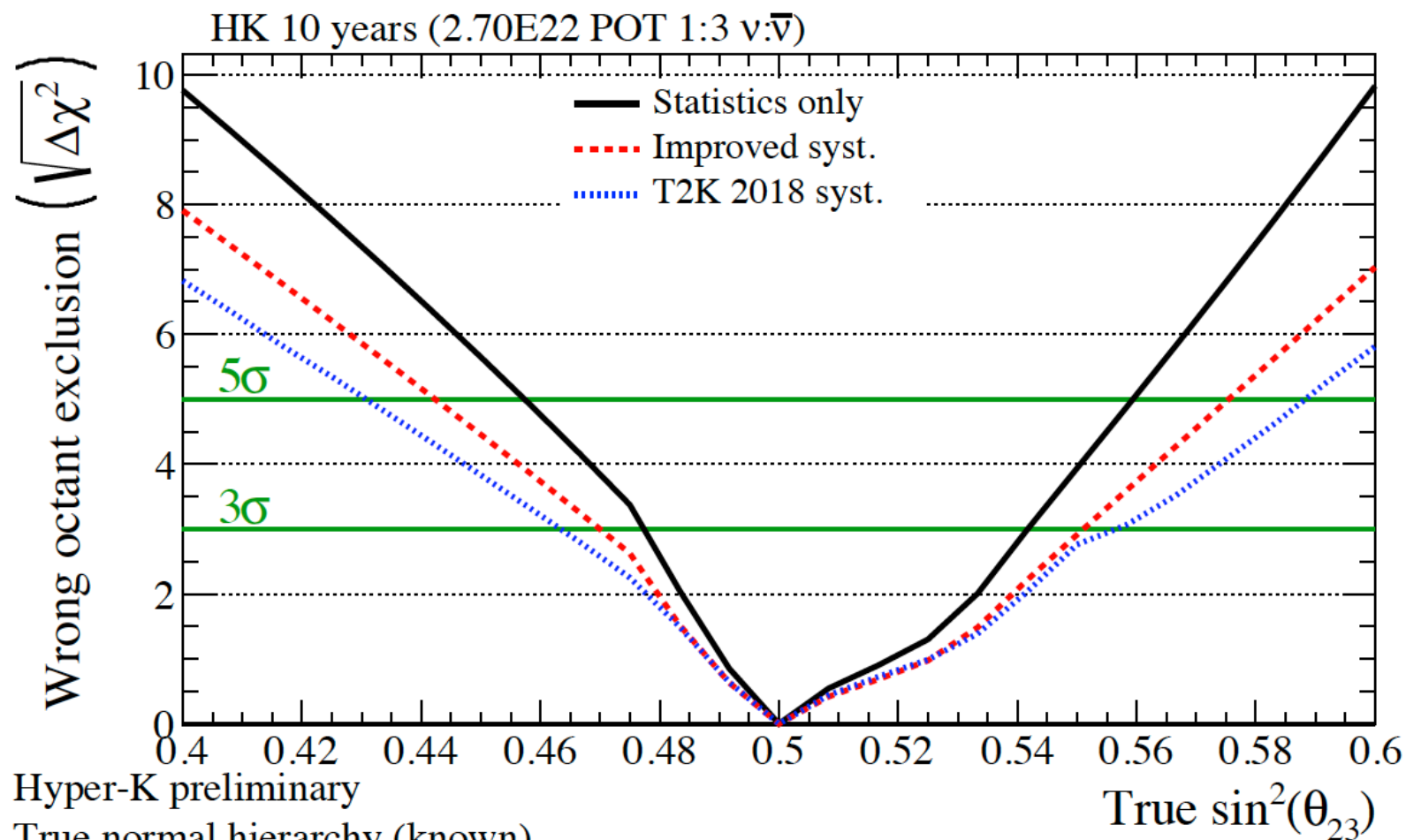
- The wrong mass ordering assumption can be excluded at 4-6  $\sigma$  significance (depending on  $\sin^2\theta_{23}$ ).  
→  $\sin\delta_{\text{CP}}=0$  can be excluded at  $5\sigma$  in the  $\delta_{\text{CP}}>0$  region for the NO case by combining HK LBL+ATM data.





# Octant degeneracy

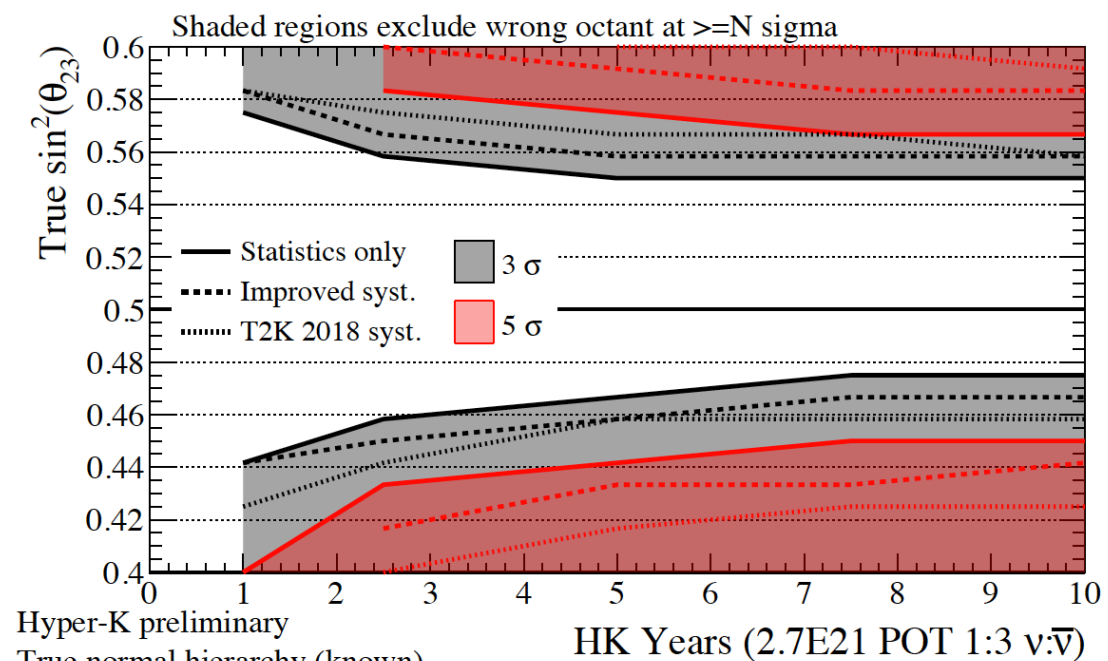
- Determination of  $\sin^2\theta_{23} > 0.5$  or  $\sin^2\theta_{23} < 0.5$  ?
  - Wrong octant assumption can be excluded with  $>3\sigma$  for  $\sin^2\theta_{23} < 0.47$  and  $\sin^2\theta_{23} > 0.55$  regions.



Hyper-K preliminary

True normal hierarchy (known)

$\sin^2(\theta_{13}) = 0.0218$   $|\Delta m_{32}^2| = 2.509\text{E-}3$   $\delta_{\text{CP}} = -1.601$



Hyper-K preliminary

True normal hierarchy (known)

$\sin^2(\theta_{13}) = 0.0218$   $|\Delta m_{32}^2| = 2.509\text{E-}3$   $\delta_{\text{CP}} = -1.601$

# Summary

- Construction of Hyper-Kamiokande is started from 2019.
  - HK Project = new 260kt WC + J-PARC upgrade
- High statistics samples for LBL measurement is expected.
  - 2300  $\nu_e$  appearance and 1900  $\bar{\nu}_e$  appearance samples in 10 years.
- Physics sensitivities are studied based on the systematic error assumptions;
  - T2K-2018 analysis based, and expected improvement assumed.
- HK can search CPV for 60% of  $\delta_{CP}$  parameter space with  $5\sigma$  significance in 10 years.
  - $\nu_e / \bar{\nu}_e$  cross-section uncertainties are dominant source of systematic errors.